An unusually brilliant transient in the galaxy Messier 85

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Historically, variable and transient sources have both surprised astronomers and provided new views of the heavens. Here we report the discovery of an optical transient in the outskirts of the lenticular galaxy Messier 85 in the Virgo Cluster. With a peak absolute R magnitude of -12 this event is distinctly brighter than novae, but fainter than type Ia supernovae (expected from a population of old stars in lenticular galaxies). Archival images of the field do not show a luminous star at that position with an upper limit of $g \sim -4.1$, so it is unlikely to be a giant eruption from a luminous blue variable star. Over a two month period the transient emitted radiation energy of almost 10^{47} erg and subsequently faded in the opical sky. It is similar to, but more luminous at peak by a factor of 6 than, an enigmatic transient in the galaxy M31. A possible origin of M85 OT2006-1 is a stellar merger. If so, searches for similar events in nearby galaxies will not only allow to study the physics of hyper-Eddington sources, but also probe an important phase in the evolution of stellar binary systems.

On January 7, 2006, the Lick Observatory Supernova Search *(LOSS)* team, in their daily circular, reported a source with apparent unfiltered magnitude of ~ 19.3 projected

2.3 kpc from the center of the lenticular (S0) galaxy Messier 85 (M85; also known as NGC 4382)*, a member of the Virgo cluster of galaxies; see Figure 1. For reasons stated below we believe that the transient lies within M85 and thus we name the source as M85 Optical Transient 2006-1 (or M85 OT2006-1 for short). Fortuitously this field was observed by the *Hubble Space Telescope* (HST) three years earlier. From the archival HST data we derive a pre-explosion limiting magnitude of F475W=−4.3.

On UT 2006 January 8 we initiated an optical photometric campaign with the automated Palomar 60-inch telescope (see Figure 2 and Table in the electronic supplementary material). The light curve with a plateau of 70 days is unlike that of type Ia supernova. The plateau duration is also too short for an outburst from a Luminous Blue Variable (LBV; η Carina).

We began a program of spectroscopic observations with the Palomar Hale and the Keck I telescopes (Figure 3). The Palomar spectrum obtained on UT 2006 January 8 did not contain any strong emission feature; the spectrum could be adequately described by a black body spectrum with effective temperature of approximately $T_{\rm eff} \sim 4600\,$K. Likewise the UT 2006 February 3 Keck spectrum was also featureless but unfortunately did not cover Hα. The UT 2006 February 23 and 24 Keck spectra showed a similar continuum but a number of emission lines were readily detected (Figure 3). Since the latter spectra were the deepest it is likely that the lines were seen due to better sensitivity.

We associate the strongest line at wavelength, $\lambda \simeq 6587\,$Å and that at $\lambda \simeq 4874\,$Å with Hα and Hβ, respectively. Accepting this identification, the mean heliocentric (peak) velocity of the pair is 880 ± 130 km s^{-1}. We were unable to conclusively identify the remaining lines but do note that the spectra of many hypergiants contain a number of unidentified[1,2] emission lines.

The systemic velocity[3] of M85 is $729 \pm 2\,$km s^{-1} and the velocity dispersion[4] in the vicinity of the optical transient is $200\,$km s^{-1}. The peak velocity of the Balmer lines is thus consistent with M85 OT2006-1 being located in M85. Accepting that M85 is the host galaxy (for which we adopt a distance of 15 Mpc, the standard distance to the Virgo

*see `http://nedwww.ipac.caltech.edu`

cluster[5]) the absolute R-band magnitude of M85 OT2006-1 is -12 mag. This peak flux is ten times brighter than the brightest nova but (at least) ten times less luminous than supernova of the Type Ia (the sort expected in a lenticular galaxy). The narrow line width of the Hα line, $\sim 350 \pm 140\,\mathrm{km\,s^{-1}}$ (see Figure 3), argue independently against both a nova and a supernova (including of type II) origin.

The Galactic foreground extinction towards M85 is negligible, $A_{\mathrm{R}} = 0.08$.[6] The source intrinsic attenuation can be derived by comparing the observed ratio of the emission lines fluxes of Hα $[(3.2 \pm 0.2) \times 10^{-16}\,\mathrm{erg\,s^{-1}\,cm^{-2}}]$ and Hβ $[(0.9 \pm 0.1) \times 10^{-16}\,\mathrm{erg\,s^{-1}\,cm^{-2}}]$ and the theoretical value of 3.05[†]. We estimate $E(B-V) = 0.14^{+0.17}_{-0.14}$ which corresponds to an R-band extinction of $0.40^{+0.48}_{-0.40}$ mag. This is to low to explain the unusual color and temperature of M85 OT2006-1 with a strongly absorbed nova, supernova or LBV.

We searched archival data from HSTe, the Spitzer Space Telescope and the Chandra X-ray Observatory with the view of constraining the progenitor. There is no evidence for a bright progenitor nor do we see tracers of massive star progenitors (see Figure 1). This finding (and the shorter duration) rule out that M85 OT2006-1 is an LBV because LBVs are amongst[1] the brightest stars, $M_{\mathrm{V}} < -8$. Along these lines we note that M85 is a galaxy composed of old stars with a possible trace of a spiral arm. We conclude that the M85 OT2006-1 likely arises from a population of stars with mass of few $M_\odot$ or smaller.

We now turn to the physical parameters of M85 OT2006-1. The bolometric luminosity flux (as traced by $4\pi d^2 \nu f_\nu$; here, f_ν is the spectral flux density at frequency ν) of M85 OT2006-1 peaks at $L_p \sim 2 \times 10^{40}\,\mathrm{erg\,s^{-1}}$. Over the first two months the total radiated energy is about $E_{\mathrm{ph}} \sim 6 \times 10^{46}$ erg. The inferred blackbody radius of the object is substantial, $R = [L_p/(4\pi\sigma_B T_{\mathrm{eff}}^4)]^{1/2} \sim 17(T_{\mathrm{eff}}/4600\,\mathrm{K})^{-2}$ AU.

The closest analog to M85 OT2006-1 is M31 RV, a bright event[8] (serendipitously) found in the bulge of Messier 31 and still lacking a satisfactory explanation. The extra-ordinary brilliance of M85 OT2006-1 (Figure 4) makes it doubly mysterious. The Galactic transient V838 Mon,[9] while considerably less luminous (see Figure 4), exhibit similar plateau light curves and redward evolution of the broad-band spectrum.

[†]Case B recombination,[7] low-density limit, $T = 5000\,\mathrm{K}$.

The distinctive physical parameters (relative to novae and supernovae; see Figure 4) and the potential connection to a fundamental stellar process (merger)[10] may warrant coining a name. We suggest the simple name *luminous red nova* with the adjectives highlighting the principal characteristics of M85 OT2006-1. Statistics (including especially the nature of the host galaxies) and follow up studies would help astronomers unravel the origin of these enigmatic transients and also study the physics of hyper-Eddington sources.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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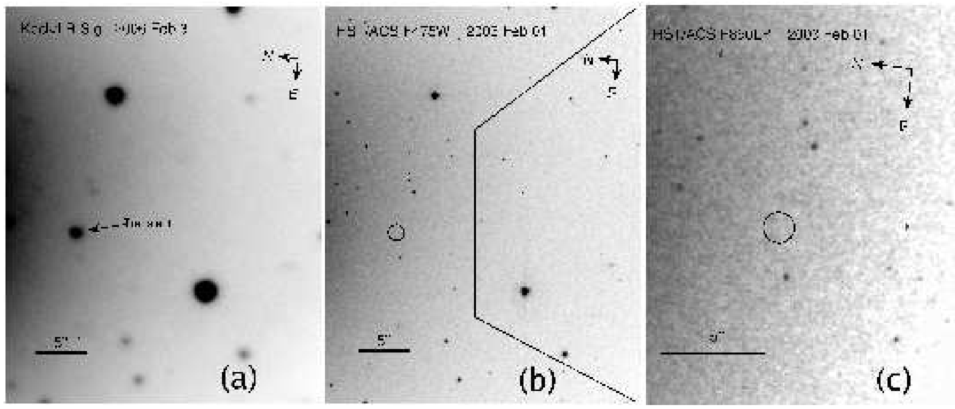

Figure 1. Optical images of the field around M85 OT2006-1 obtained at two epochs. Data were obtained with the Low-Resolution Imager and Spectrograph (LRIS;[11]) at Keck (a) on Feb 3, 2006, and the Advanced Camera for Surveys aboard the Hubble Space Telescope (b - F475W filter; c - F850LP filter) on Feb 1, 2003. The event is located about 30" from the center of M85 at α=$12^{\rm h}25^{\rm m}23.82^{\rm s}$ and δ=$18^\circ10'56.2''$ (J2000). After registering the Keck image to the HST image (rms of the transformation was 40 mas) we were able to place the following limits for a pre-cursor object (progenitor star): 26.8 mag in the F475W filter (exposure 750 s) and 24.7 mag in the F850LP filter (exposure time 1150 s). These limits exclude an LBV[1] origin (for which $M_{\rm V} \sim -8$ mag). Furthermore, we find no evidence for young stars (supergiants, clusters and HII regions). An analysis of Spitzer Space Telescope Infared Array Camera data obtained on Dec 21, 2004, result in 3σ upper limits of 25, 30, 60 and 75 μJy at 3.6, 4.5, 5.8 and 8.0 μm, respectively. *LOSS* observed M85 two hundred and twenty times over 2000–2006. We found no transient at the position of M85 OT2006-1 to (roughly R-band) magnitudes ranging from 20 to 21. No X-ray emission was detected in a *Chandra* X-ray Observatory observation[12] obtained in June, 2002, with a flux upper limit of 2.7×10^{-4} cnt s^{-1} in the 0.3–10 keV band.

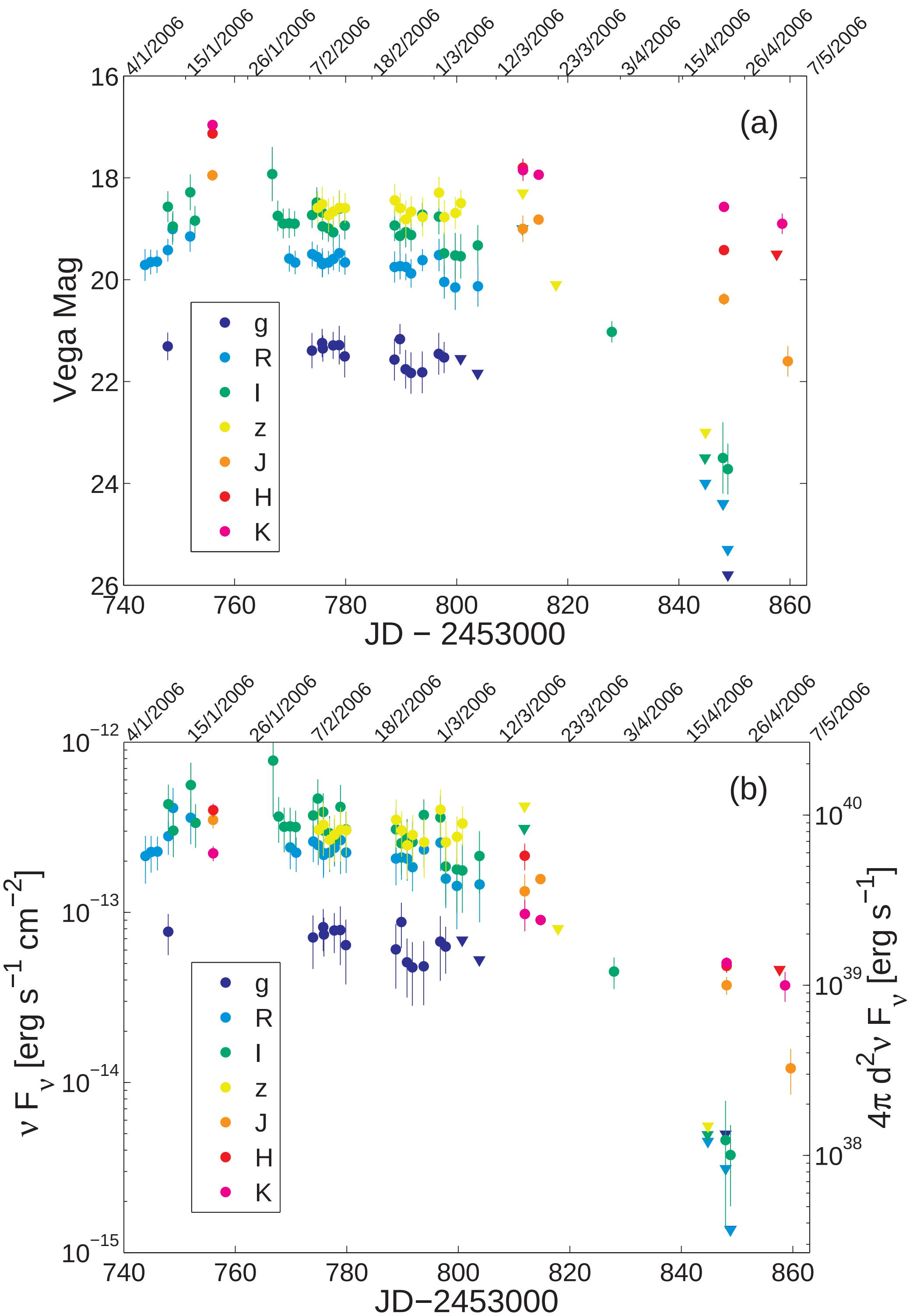

Figure 2. Temporal evolution of M85 OT2006-1. (a) observed light curve uncorrected for Galactic foreground extinction and (b) νf_ν including foreground extinction correction of $A_V = 0.08$.[6] Data for the plots are given in Photometry Table of the electronic supplement and come from the following sources: Palomar 60-inch (P60; $gRIz$), the Large Format Camera (LFC) on the Palomar Hale 200-inch (P200; zRI), the Widefield Infrared Camera (WIRC) on P200 (JHK), LRIS on the Keck-I 10-m telescope (gRI), Persson's Auxilary Nasmyth Infrared Camera (PANIC)

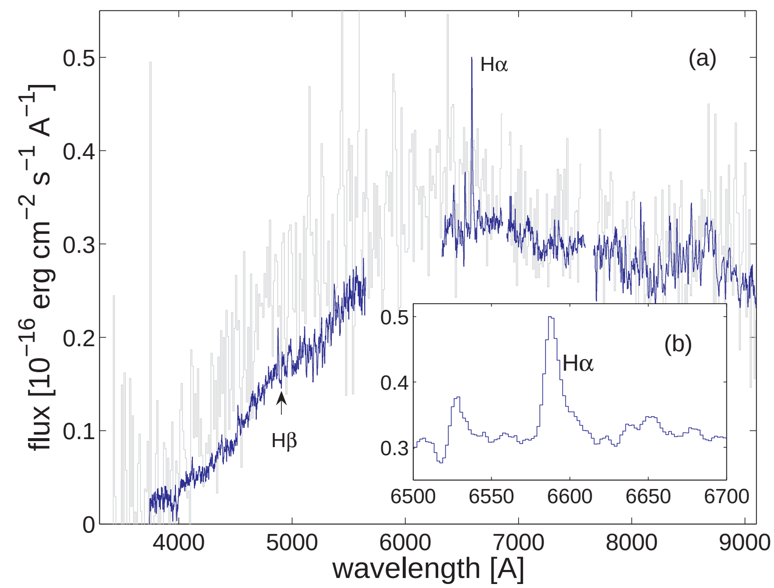

Figure 3. Optical spectra of M85 OT2006-1. Data were obtained with the Double Beam Spectrograph[13] (DBSP) at the Palomar Hale 200-inch telescope (grey line, 1800 s integration, Jan 8.53 UT, 2006) and Keck/LRIS (blue line, 3000 s, Feb 24.59 UT, 2006). Not strong emission or absorption features are seen in the (native) DBSP spectrum. Specifically we place a limit of 6×10^{-16} erg s^{-1} cm^{-2} for an emission line in the vicinity of Hα. In the LRIS red channel spectrum the brightest emission feature is at $\lambda = 6587$ Å (flux of $(3.2 \pm 0.2) \times 10^{-16}$ erg s^{-1} cm^{-2}) which we identify with redshifted Hα. The velocity of the line center is 1020 ± 150 km s^{-1} (see inset). On the blue side, the strongest feature is at $\lambda = 4875$ Å corresponding to redshifted (700 ± 100 km s^{-1}) Hβ (flux of $(0.9 \pm 0.1) \times 10^{-16}$ erg s^{-1} cm^{-2}) . The equivalent widths are 10 ± 1 Å (Hα) and 5 ± 1 Å (Hβ). The full width at half maximum (FWHM) of the Hα line, after accounting for the instrumental FWHM, is 350 ± 140 km s^{-1}. In addition we detect the following emission lines (central wavelengths, typical uncertainty of 1 Å; and fluxes, unit of 10^{-16} erg s^{-1} cm^{-2}): 4115 Å (0.3 ± 0.1), 6428 Å (0.9 ± 0.1), 6527 Å (1.5 ± 0.4), 8079 Å (0.8 ± 0.1) and 8106 (0.7 ± 0.1). Further LRIS spectra were obtained on UT 2006 February 3 and 23 (not shown here). The February 3rd LRIS spectrum did not include the Hα wavelength. For this spectrum, using a sliding 10 Å window we were able to set a 3-σ upper limit of $\lesssim 6 \times 10^{-18}$ erg cm^{-2} s^{-1} in the vicinity of Hβ.

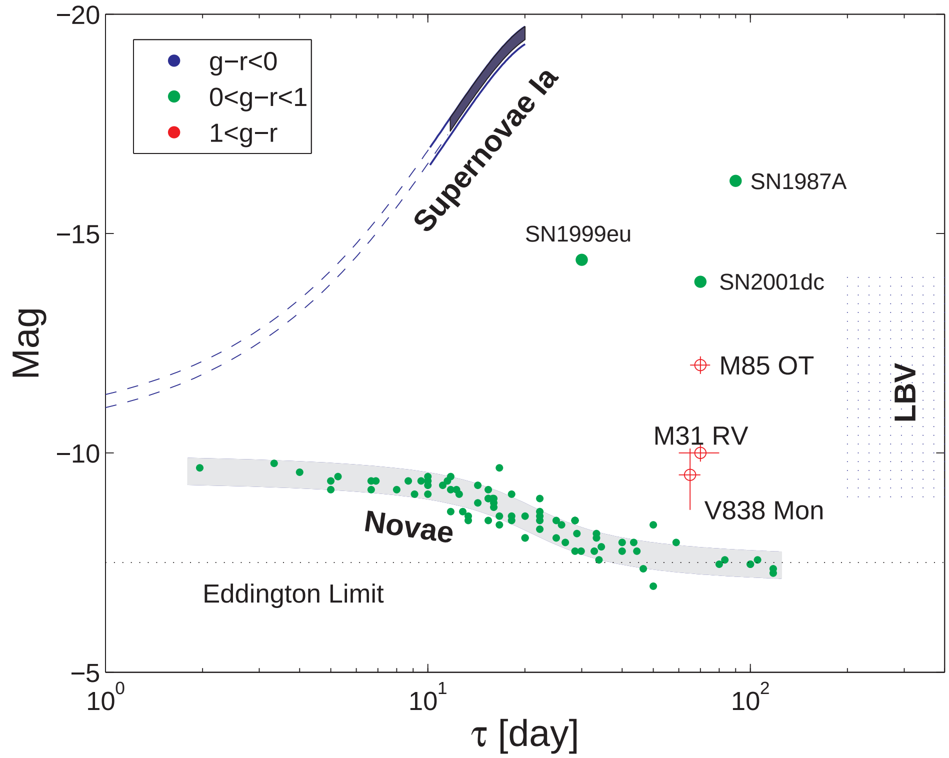

Figure 4. Phase space of cosmic explosive and eruptive transients. The vertical axis is the peak brightness in the R-band and the horizontal axis is the duration of the event (τ). Events are represented by circles with the color at peak magnitude coded as follows: blue ($g - r \lesssim 0$), green ($1 \gtrsim g - r \gtrsim 0$) and red ($g - r \gtrsim 1$). M85 OT2006-1 and the M31 RV[8] clearly stand out in this figure in the following respects: (*i*) brighter than novae but (*ii*) less luminous than most supernovae (especially of type Ia indicated with a 2σ brightness band) and (*iii*) distinctly red color when compared to sub-luminous core collapse supernovae (such as SN 1987A). Finally, the two events, unlike LBVs and core collapse supernvoae, do not arise in star-forming regions. For any reasonable progenitor mass, both events exhibit hyper-Eddington peak luminosities, similar to the sources V838 Mon.[14,10] Furthermore, both sources also characterized by low expansion velocity ($< 1000\,\mathrm{km\,s^{-1}}$) and a strong redward evolution of the peak frequency. For these objects, τ, is the "plateau" time scale. For novae, τ is the time scale in which the nova fades by two magnitudes, t_2. Filled circles show the positions of 82 novae observed[15,16] in Messier 31 (assuming[17] $V - R = 0.56$ at peak). The brightest stars in our Galaxy are highly variable but these objects (marked "LBV") are clearly distinguished by long variability timescales and a high quiescent magnitude. The dashed line ($R = -7.5$ mag) is the Eddington limit for a $1\,M_\odot$ G-type star.